

## Status of the Neutrino Factory and Muon Collider R&D

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For the  
Muon Collaboration

## Outline

Neutrino factory/muon collider overview

Key technical systems:

Targetry

Phase rotation/capture

Muon cooling

Absorbers

RF

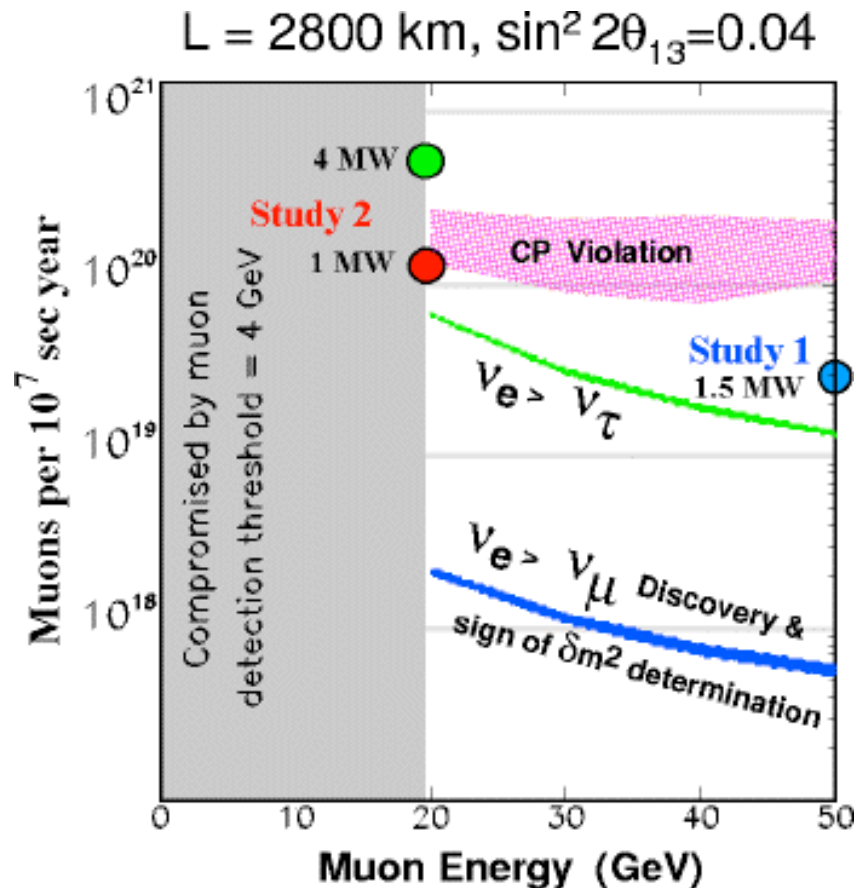
Acceleration

Storage ring

Conclusions

# Status of the Neutrino Factory and Muon Collider R&D

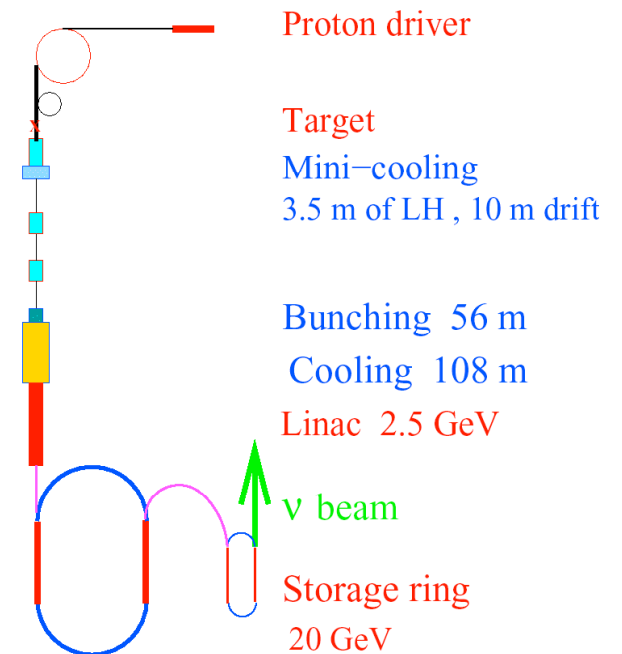
## Overview/Schematic of a neutrino factory



Physics reach

Induction linac No.1  
100 m  
Drift 20 m  
Induction linac No.2  
80 m  
Drift 30 m  
Induction linac No.3  
80 m

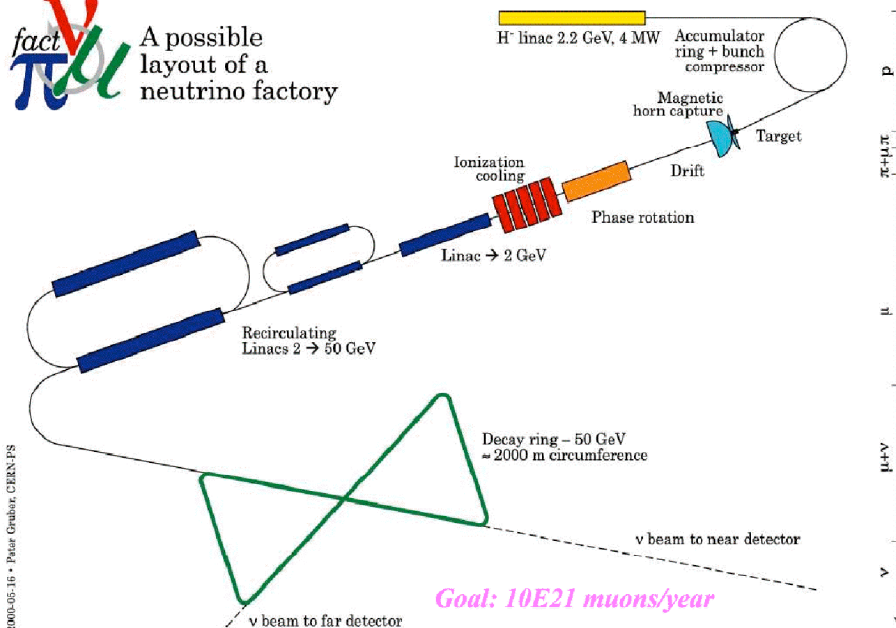
Recirculating Linac  
2.5 – 20 GeV



US scheme (study II)

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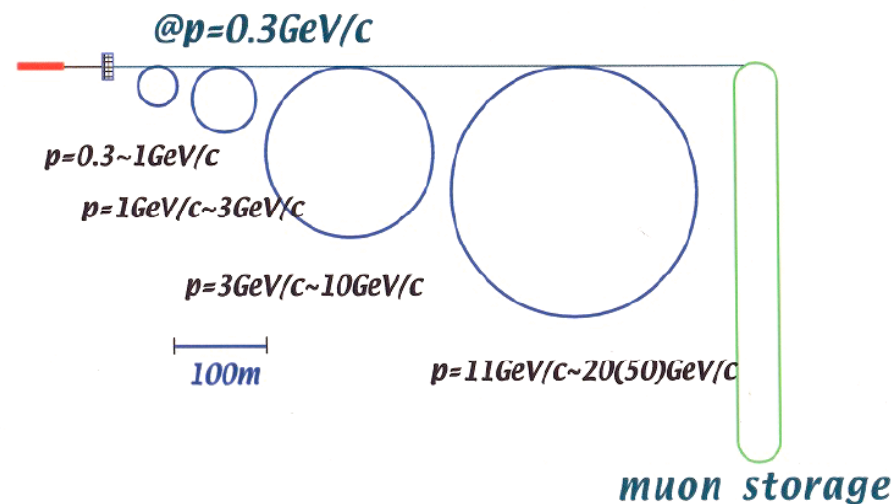
fact  $\pi$   $\mu$  A possible layout of a neutrino factory



### CERN scheme

Recycled LEP components in SPL  
Low Frequency RF for cooling  
(88 MHz = large aperture!)  
"Bowtie" storage ring  
Superconducting linac/RLA's for acceleration

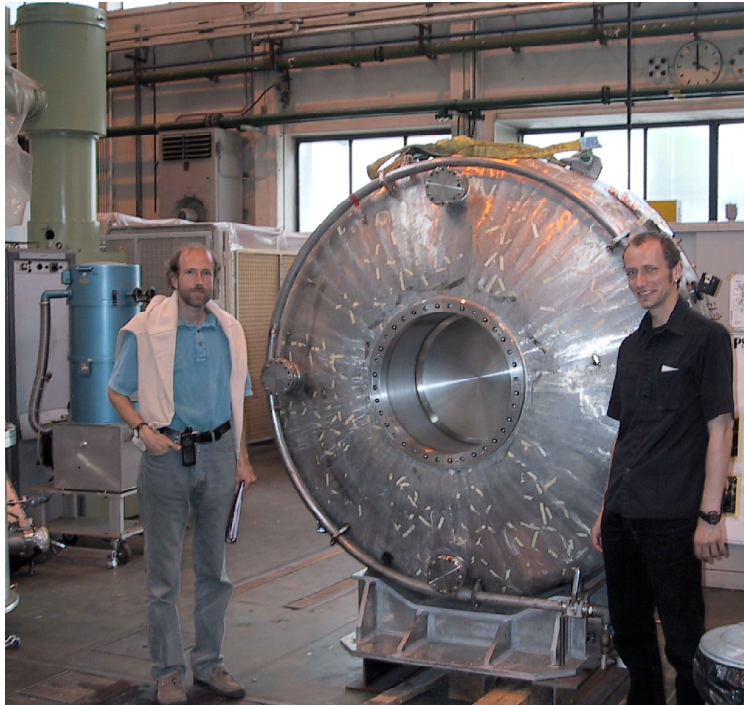
(1) Low Freq. ( $\sim$  MHz) & High Gradient RF  $E > 1 \text{ MV/m}$   
(2) Acceptance: Trans.:  $0.01-0.02 \pi \text{ m.rad}$ , Long.  $\Delta P/P \sim \pm 50\%$



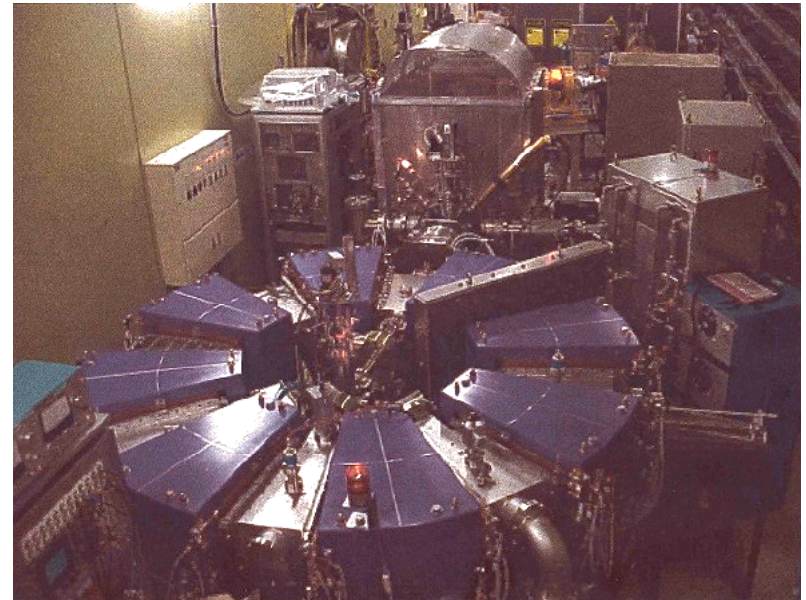
### KEK scheme

Large acceptance FFAG's.  
No phase rotation or cooling (may add).  
R&D issues: RF, Injection/extraction, magnet design, dynamic aperture.  
Proof of Principle FFAG tested successfully in June 2001 at KEK.



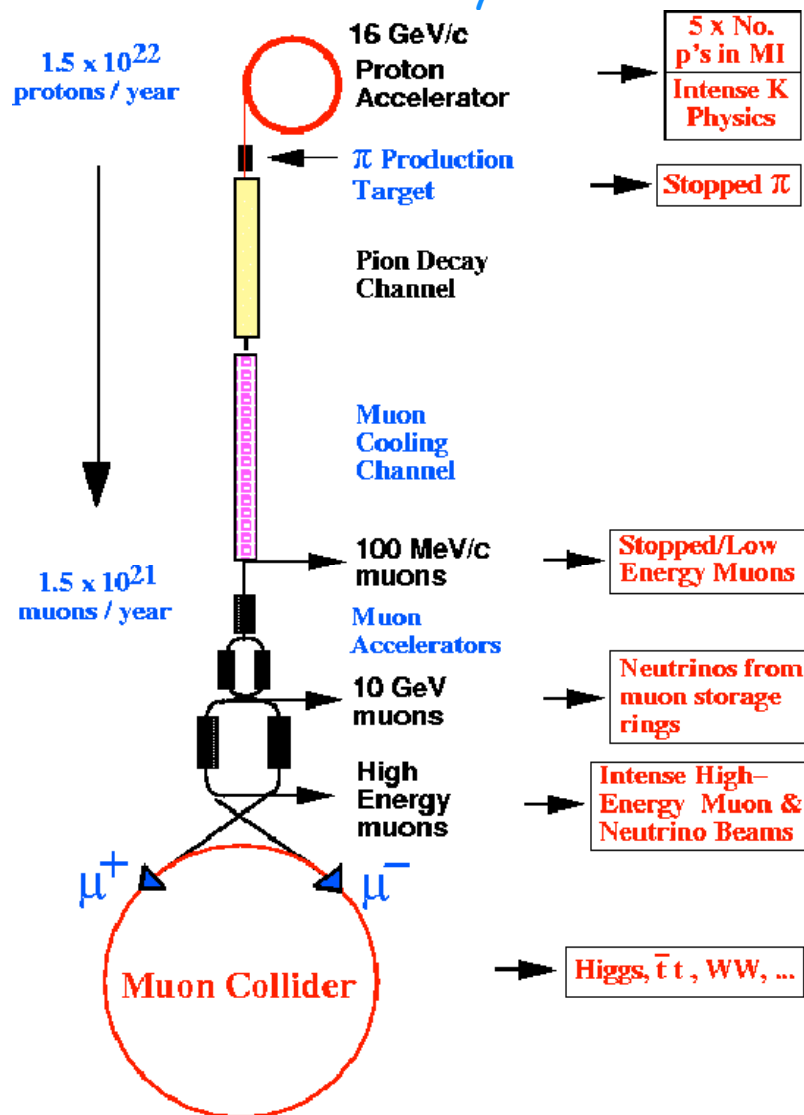


CERN 88 MHz RF cavity



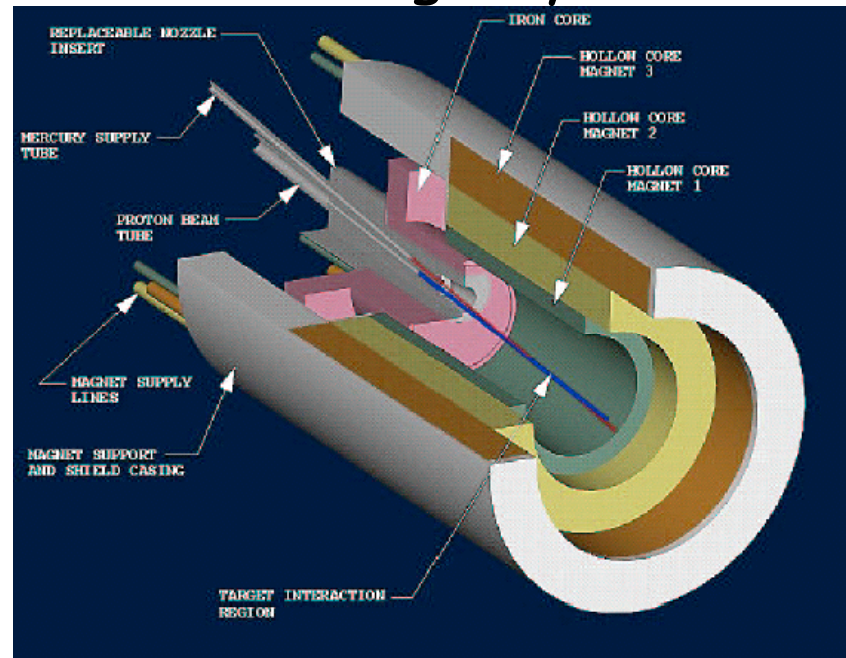
Proof of Principle FFAG

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schematic of a muon collider

## Targetry

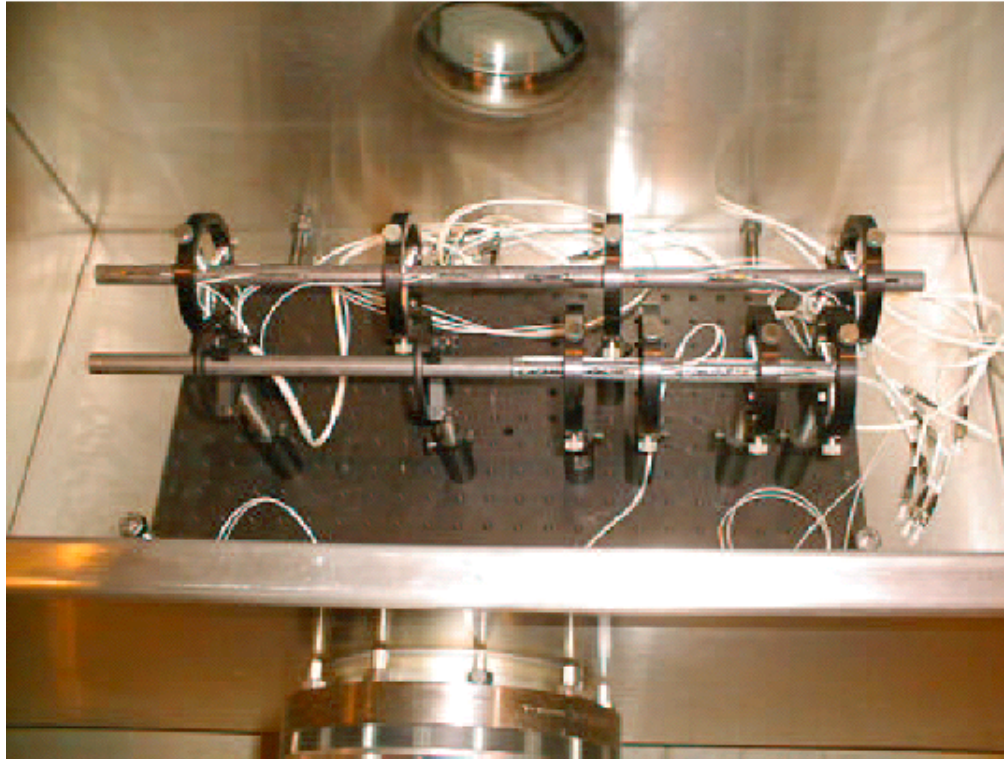


*Kirk McDonald et. Al., BNL E951*

Capture Pions in a 20 T solenoid field/1.25 T decay channel  
 Carbon target is feasible for  $\sim 1.5$  MW proton beam power  
 Prefer higher Z material for maximum pion (muon) yield  
 Static High-Z target would melt, need moving target  
 Free mercury jet could allow beam power of 4 MW  
 Capture solenoid subject to intense radiation



## Solid target experiments

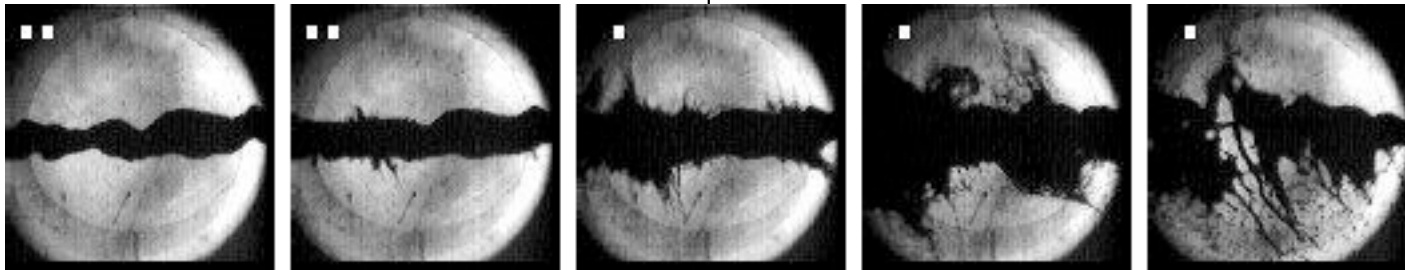
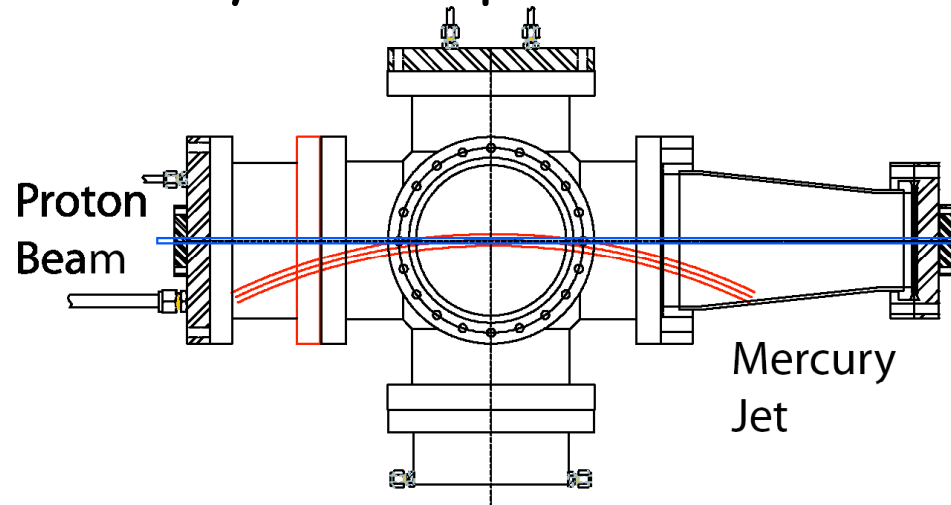


Carbon composite, Aluminum, Ti90Al6V4, Inconel, Havar tested.

Carbon-Carbon composite has almost zero thermal expansion can withstand beam induced pressure waves. Sublimation may be suppressed in He atmosphere

Radiation damage is limiting factor, ~12 weeks in 1 MW beam

## Mercury Jet experiment at AGS



1 cm diameter mercury jet in  $2 \times 10^{12}$  protons from AGS at  $t=0, 0.75, 2, 7, 18$  ms

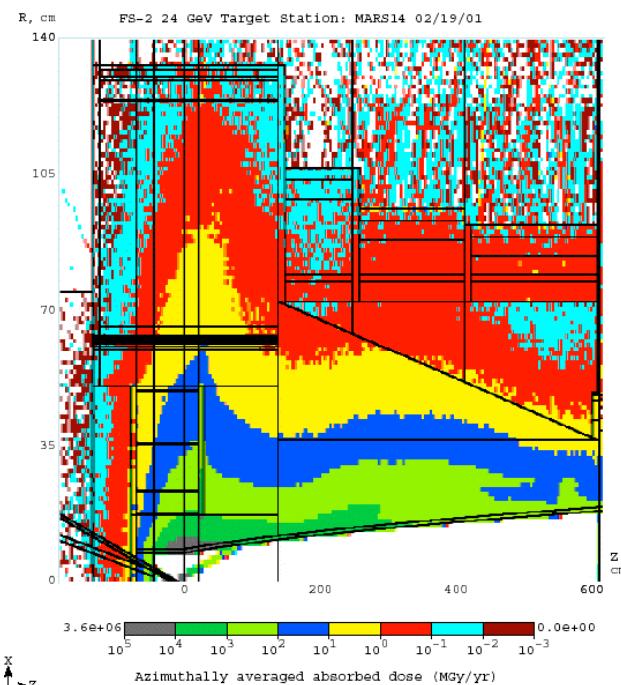
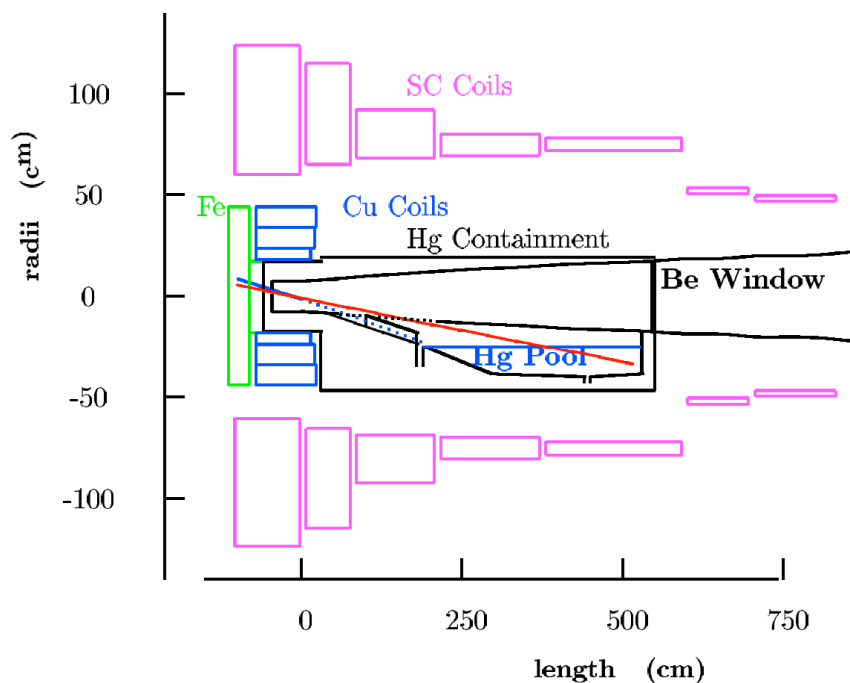
Dispersal velocity  $\sim 50$  m/s, scales with intensity. Dispersal is not destructive.

No solenoid field, should be OK if nozzle is inside field.

CERN/Grenoble experiment (13T) suggests magnetic field damps surface waves.

Plan to test mercury jet target in real solenoid (15T).

## Capture solenoid



Combination of outer superconducting coils (14T), in lower radiation areas and copper coils (6T), closer to target.

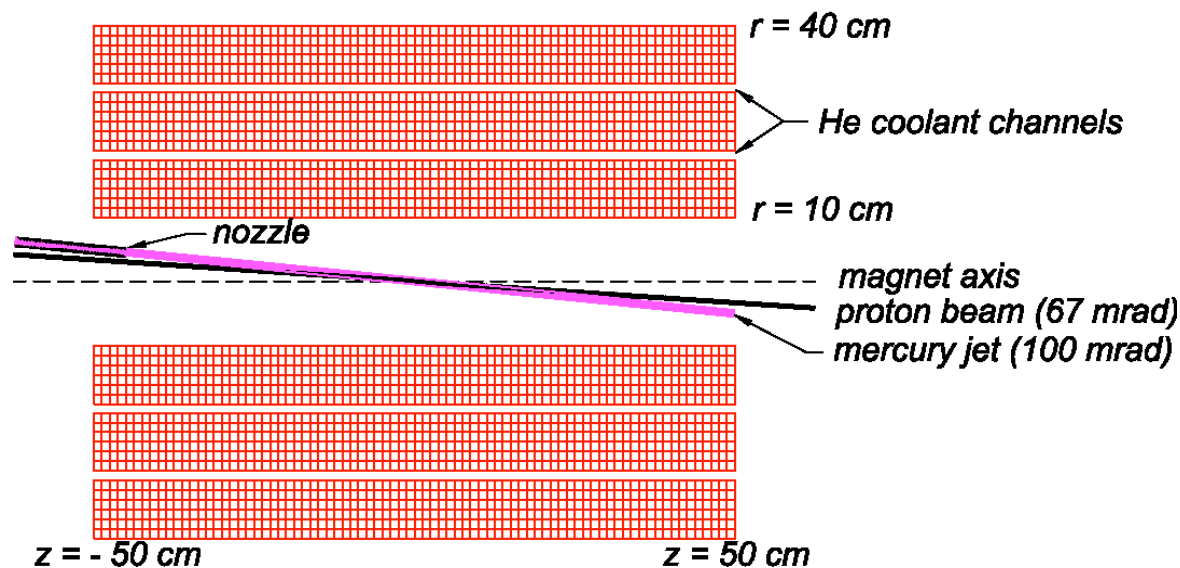
Hollow-conductor water-cooled copper coils.

Both coils shielded by tungsten-carbide/water.

Too expensive to prototype at 20T, so...

## Targetry test solenoid

14.5-T Pulsed Magnet (using all 3 coils)  
5- or 10-T magnet using inner 2 coils



Propose 14.5T pulsed normal-conducting magnet for mercury target experiments.

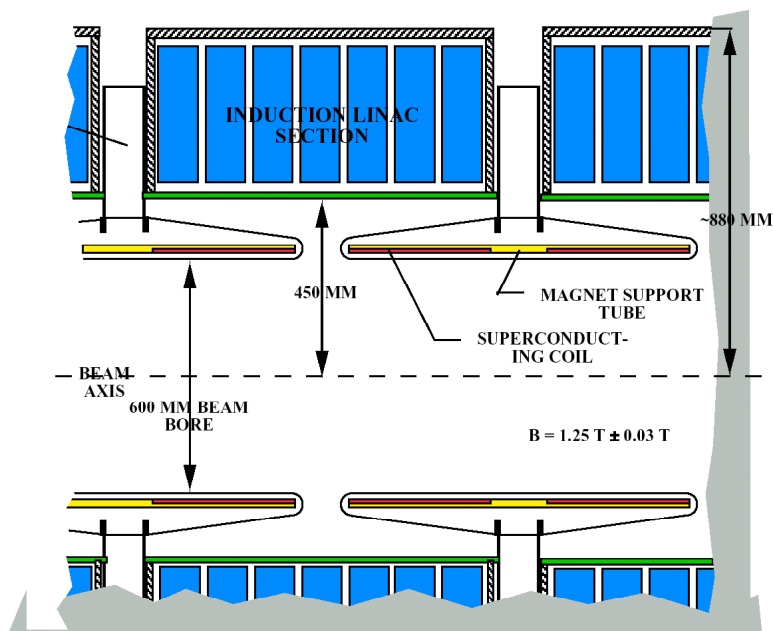
Phased approach, 5 or 10 T using inner coils.

14.5 T with all coils,  $H_2$  cooling.

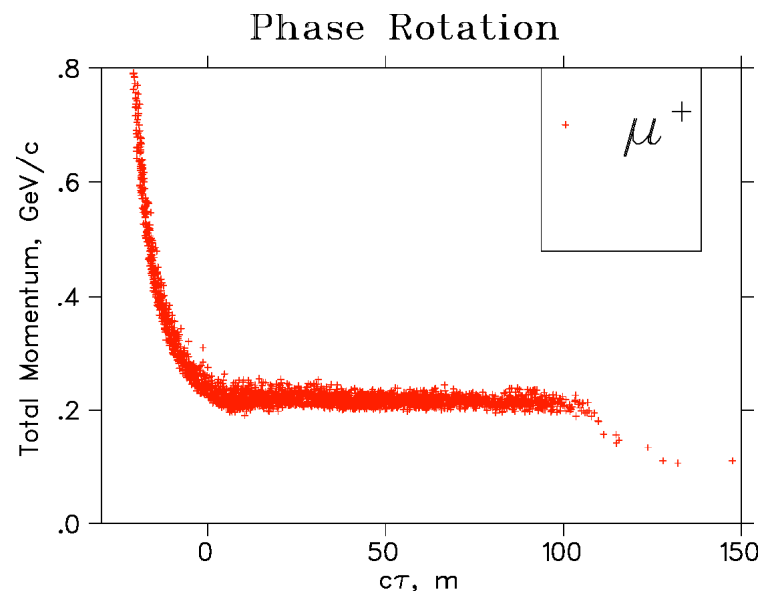
Reasonable to extrapolate results to 20T.

Plan to build target test experiment in existing area at BNL.

## Phase rotation (Induction Linac)



(J. Fockler, M. Green, S. Yu, et. Al.)



Large energy spread from target.

Drift section allows energy-time correlation to develop.

Apply acceleration with opposite correlation for core of beam.

Result is smaller energy spread but over long distance.

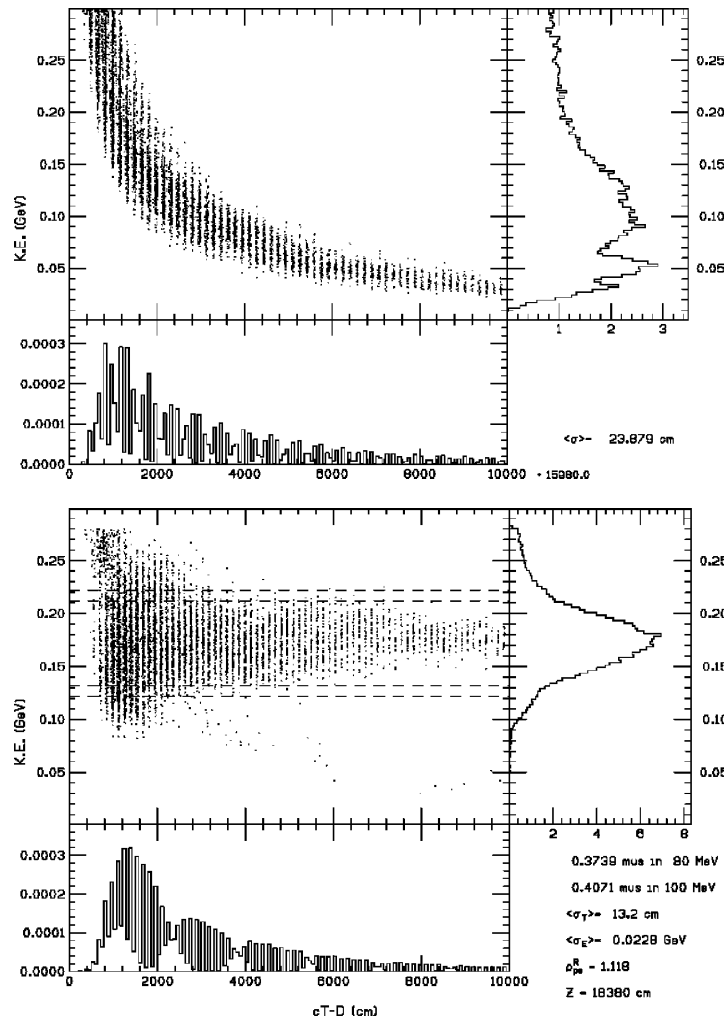
Must be bunched for capture in RF bucket.

Induction linac is fairly standard (e.g. DARHT\*), except for solenoid channel.

\*Dual-Axis Radiographic Hydrotest



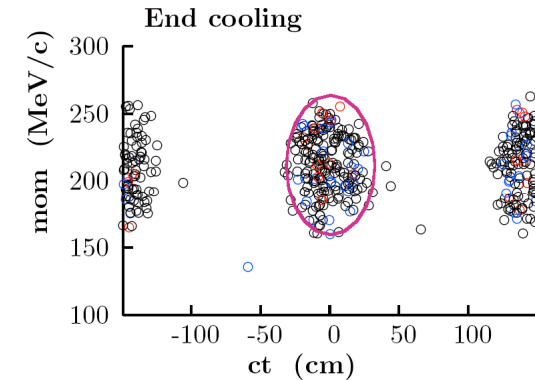
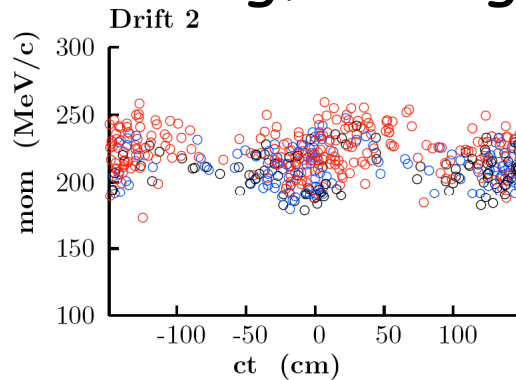
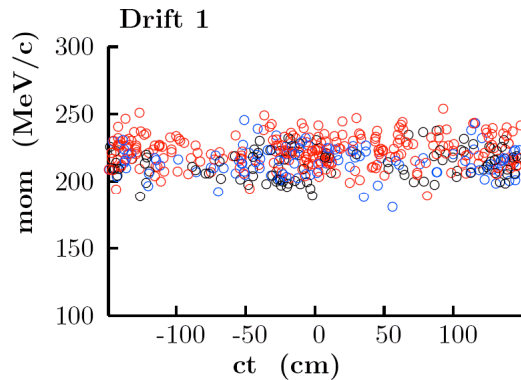
## RF Phase rotation (*Neuffer et. Al.*)



- After drift plus adiabatic buncher, beam formed into string of  $\approx 200$ -MHz bunches
- After  $\approx 200$ -MHz RF rotation, beam formed into string of equal-energy bunches matched to cooling RF acceptance

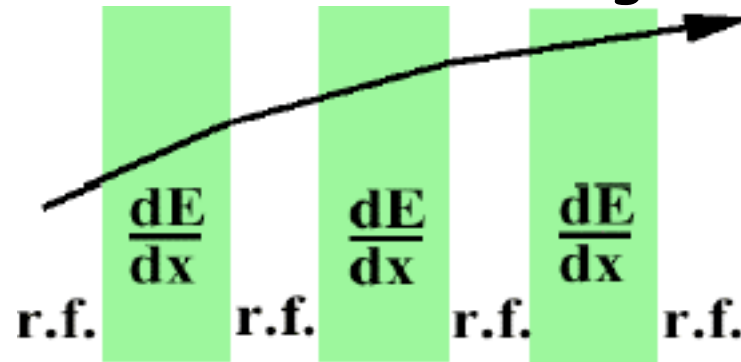
RF phase rotation looks very promising, may save \$200M of cost of neutrino factory.

## Bunching, cooling



Phase rotated beam is bunched and captured in RF channel before cooling.

## Ionization cooling

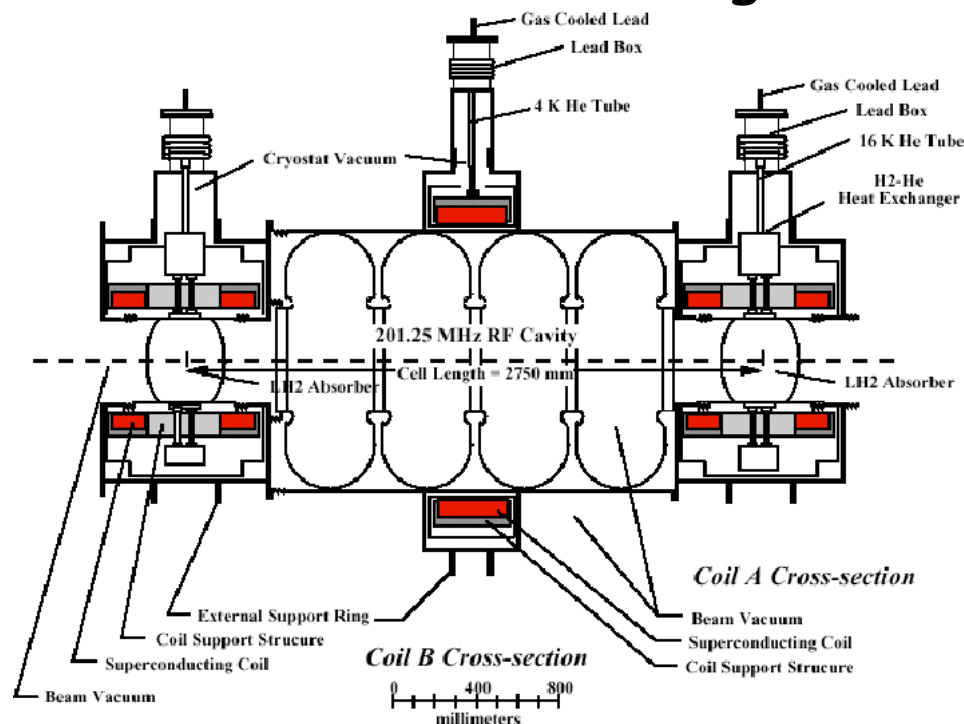


So simple it must work!

Demonstration of realistic ionization cooling is core purpose of [Mucool](#) and [MICE](#)

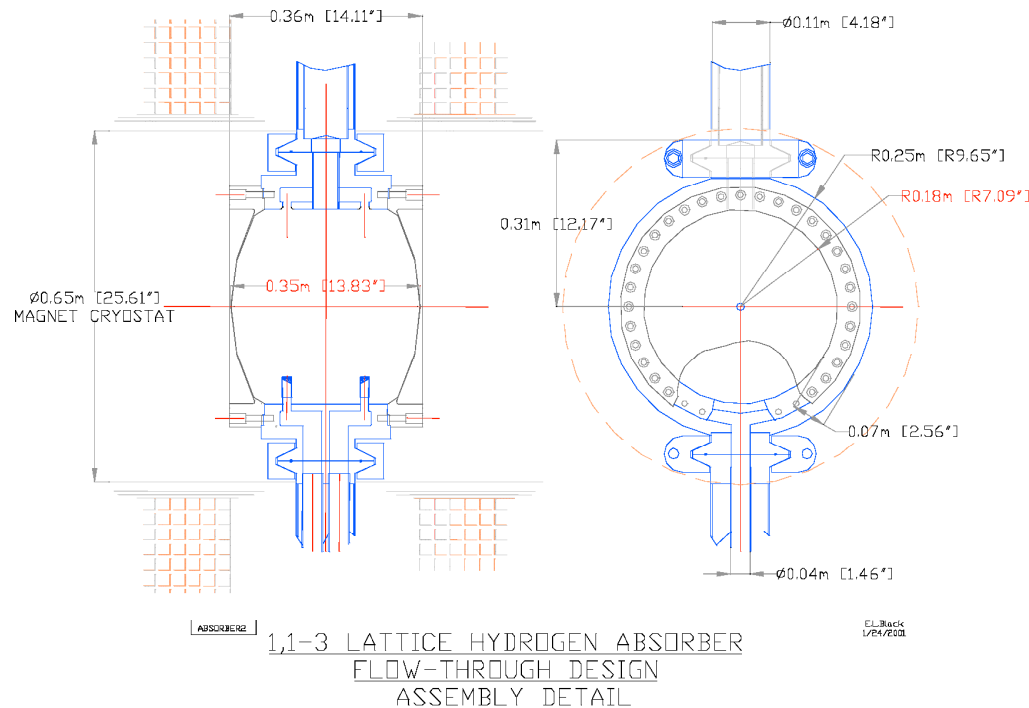
Involves absorbers, RF, solenoid channel, instrumentation, integration, etc.

## Schematic of a cooling cell



Periodic **superconducting solenoid** lattice with field flips.  
 Low Z **absorbers** for ionization cooling with minimum scattering.  
 Containment **windows** (and secondary containment if LH<sub>2</sub>).  
 High gradient **RF** for reacceleration, perhaps with Be Foils.  
**Instrumentation** and diagnostics.

## Absorbers



*FNAL/IIT/KEK/NIU/Osaka/UIUC/UMiss*

Convection or forced-flow LH2 absorber between thin Aluminum windows.

Assembly resides inside superconducting solenoid, between RF cavities.

Active R&D program to test prototype absorbers and windows.

Aluminum windows as thin as 125  $\mu\text{m}$  successfully machined at U. Miss.

Rupture tests verify numerical analysis, (essential for LH<sub>2</sub> safety requirements)

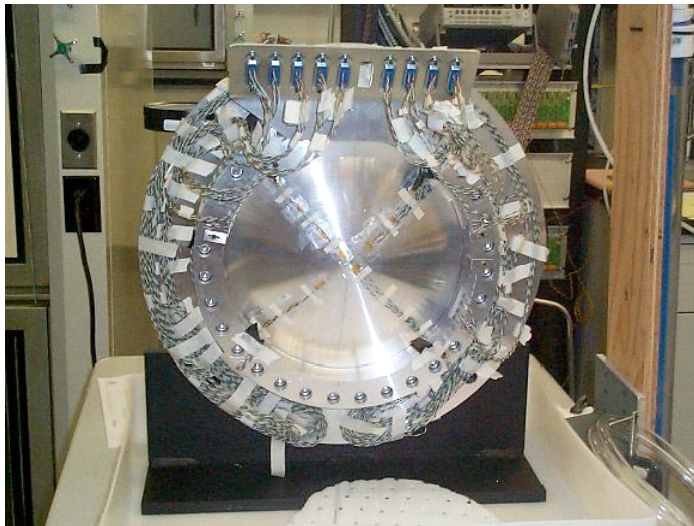




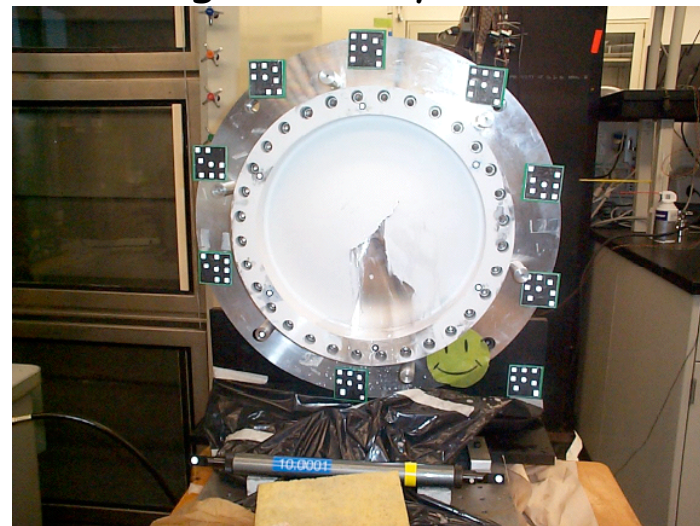
Al windows machined at U. Miss.



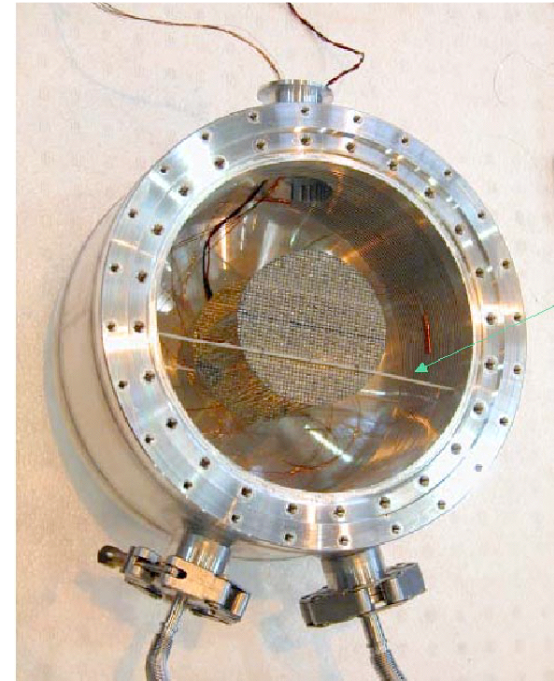
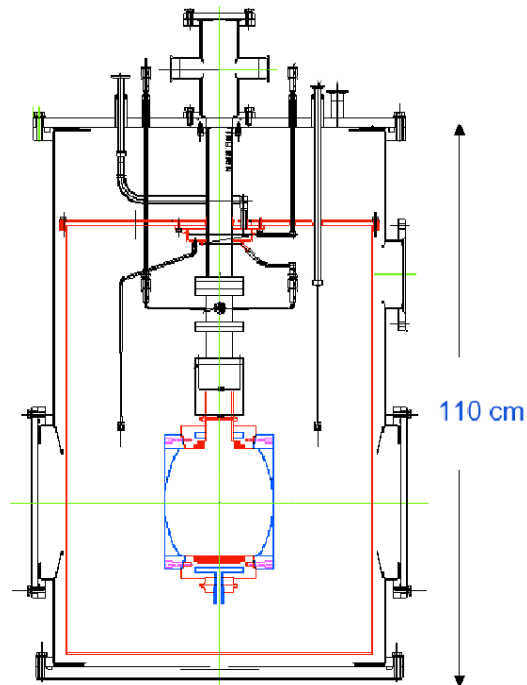
Photogrammetry test at IIT



Strain gauge test



Rupture test



## KEK convection absorber test

Simpler design and construction

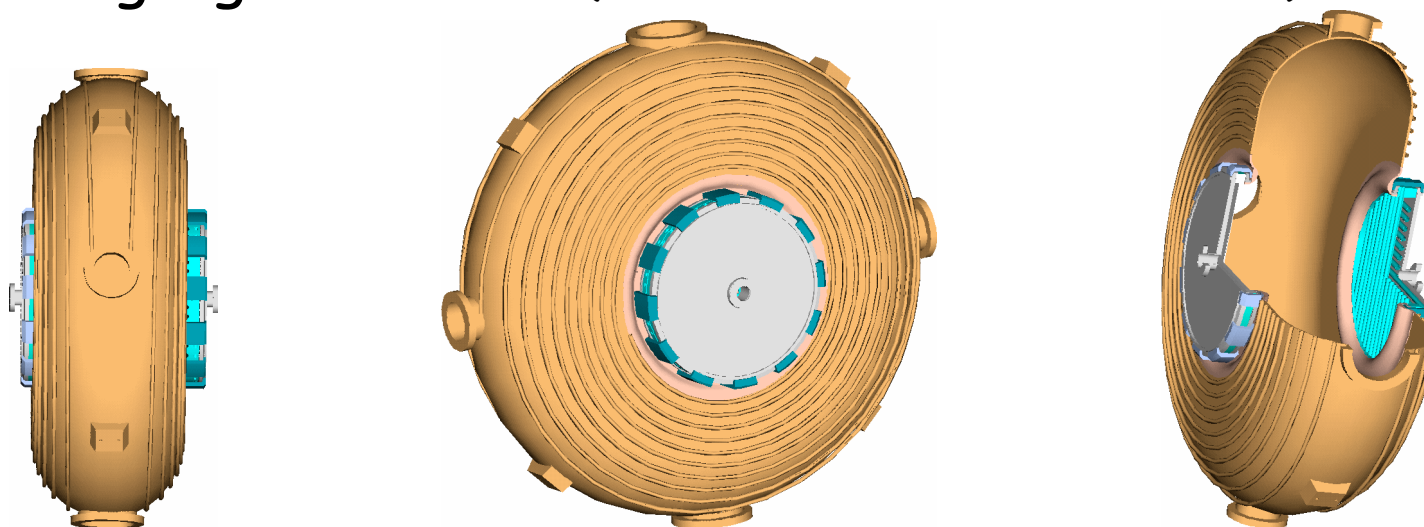
Has been tested with cryogenics (liquid neon)

Future experiments will test heat transport capacity

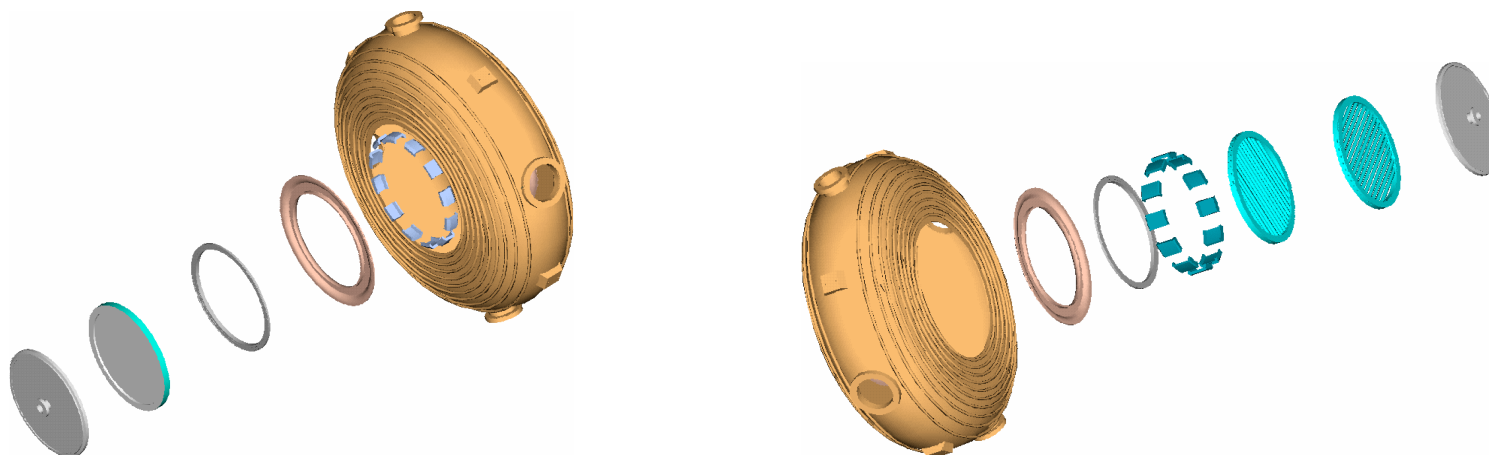


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### High-gradient RF (ANL/FNAL/IIT/LBNL/U.Miss)

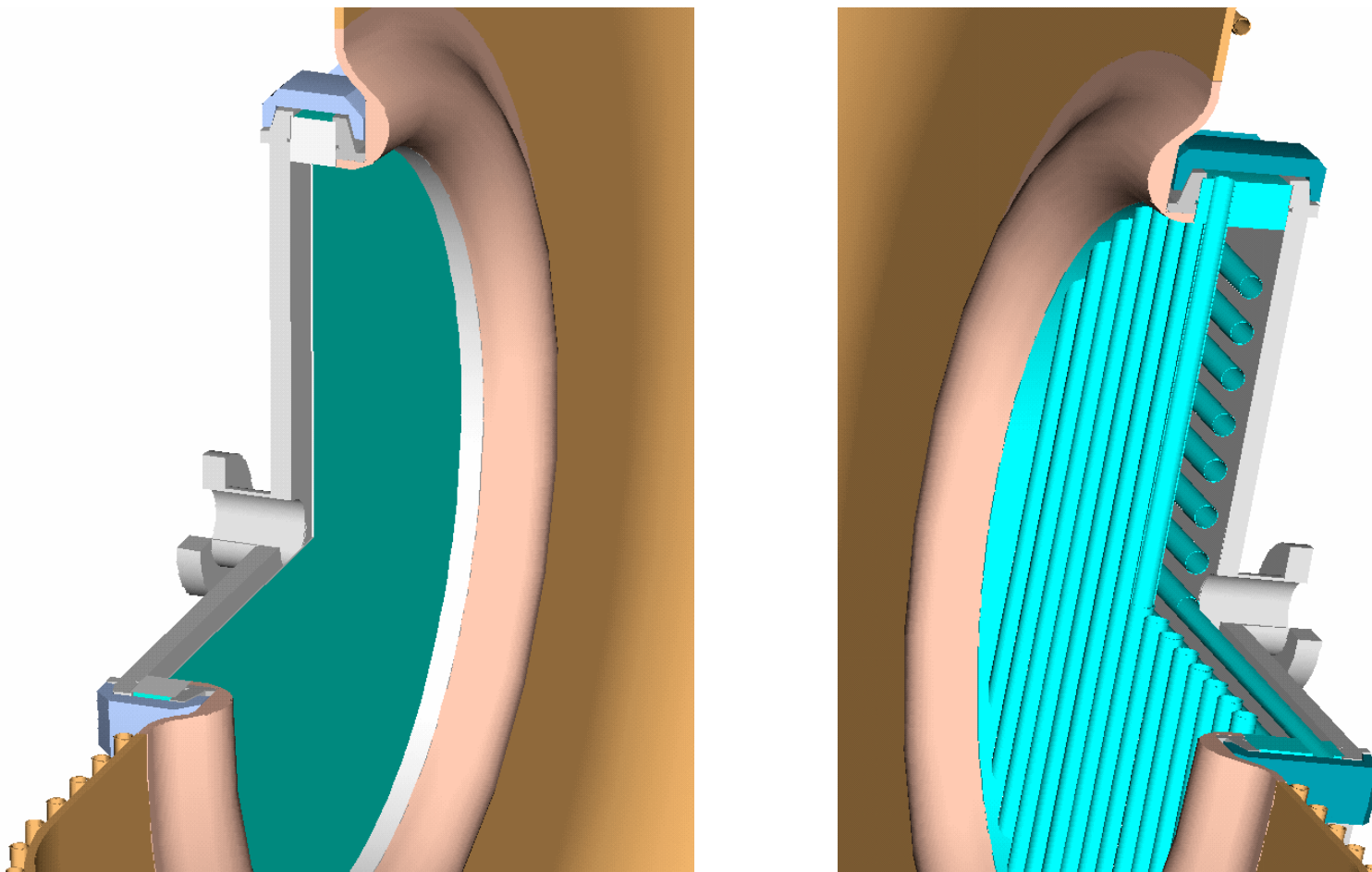


201.25 MHz cavity conceptual design



Exploded views showing foil and grid mounting hardware

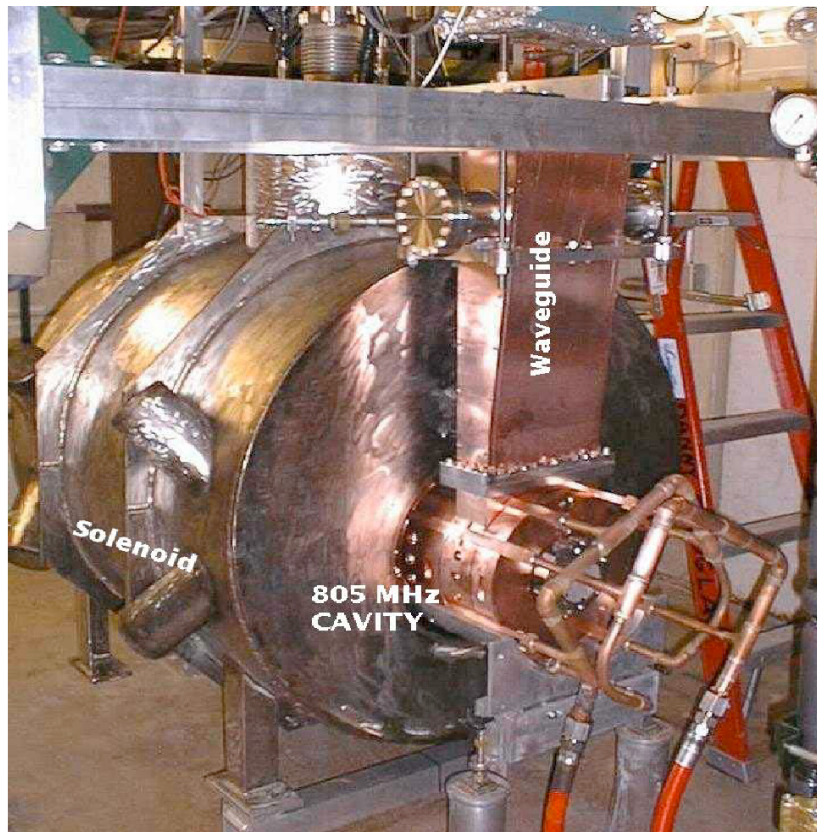
## Foils and Grids



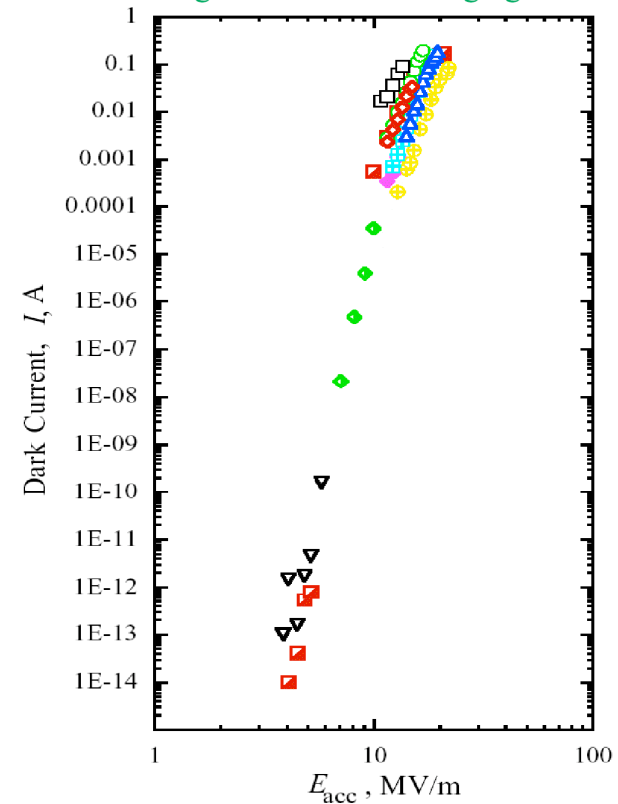
Detail views of foil and grid mounting assemblies



## Testing in progress at 805 MHz



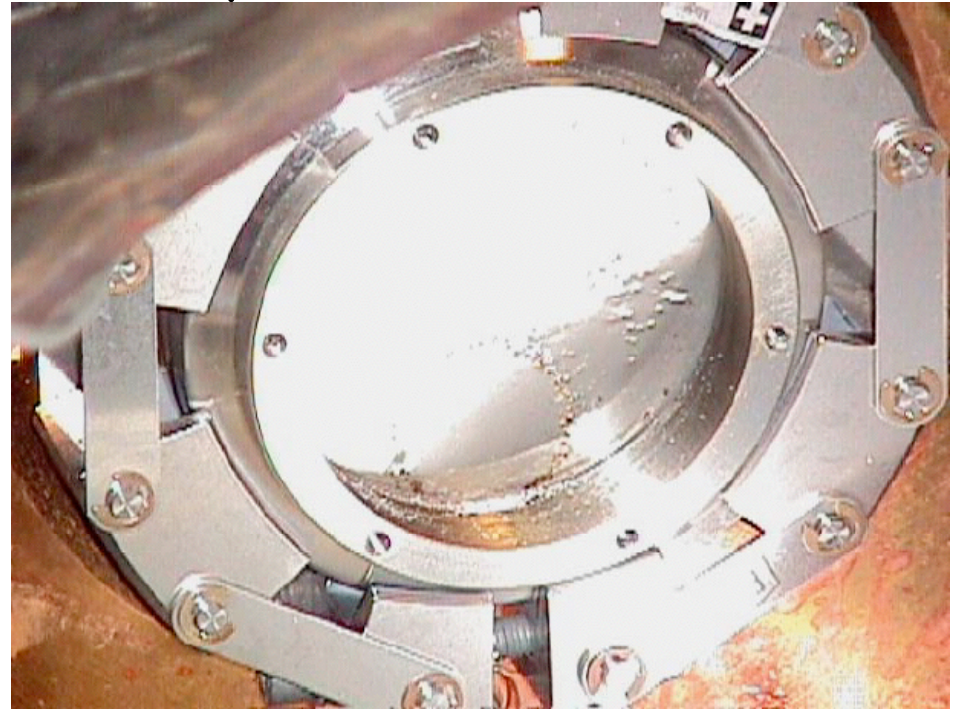
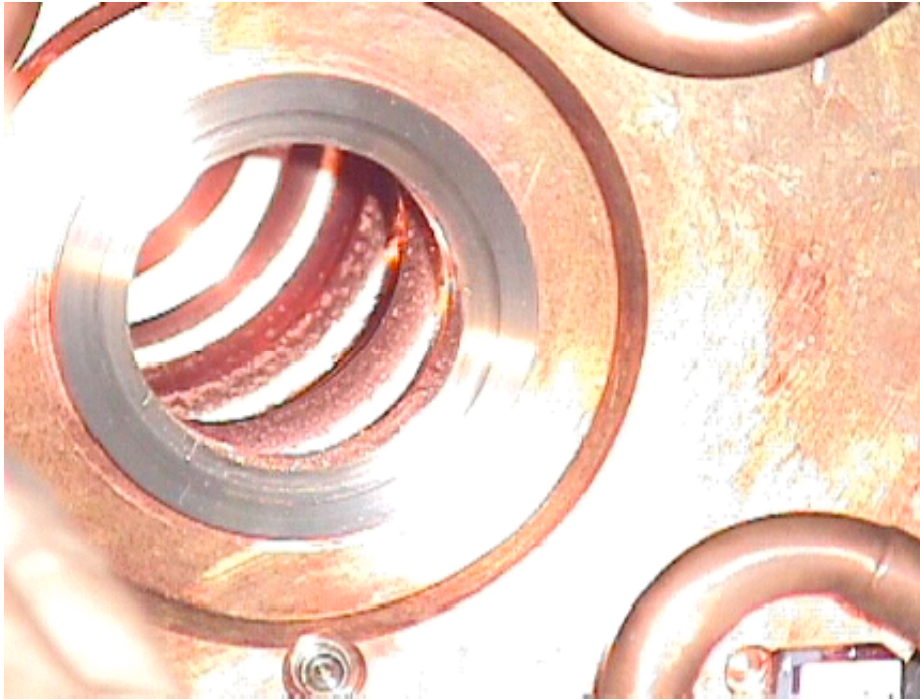
- See large dark current at high gradients:



*Norem et.al.*

FNAL Open-cell cavity conditioned to 54 MV/m surface field.  
Significant surface damage and high dark currents.

## FNAL open-cell cavity test



Damage to exit foil when solenoid field was on.

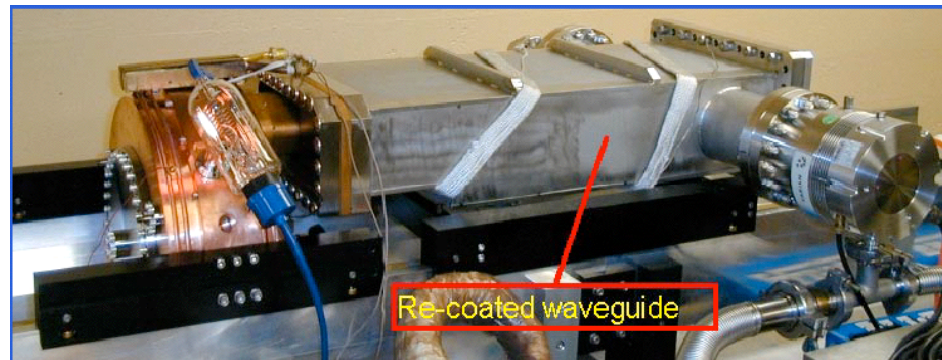
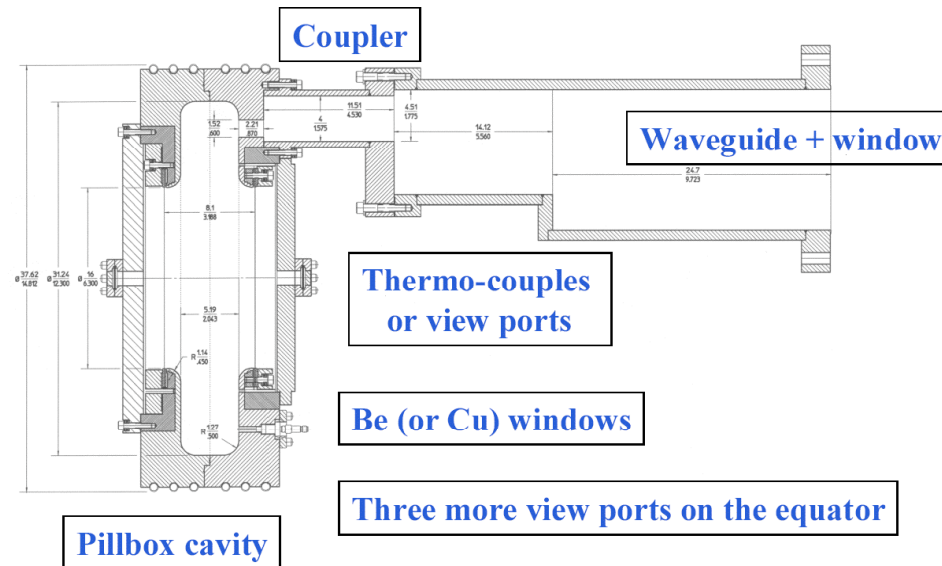
Probably "imaging" of emitters on irises.

We need to understand these effects.

May be able to reduce by surface treatments, SCRF type cleaning procedures.



# Now testing single cell LBNL/U.Miss. 805 MHz cavity



Cavity can be fitted with Be foils or Al grids to study breakdown and dark currents. Has been conditioned to 34 MV/m with relatively little sparking (no magnetic field).

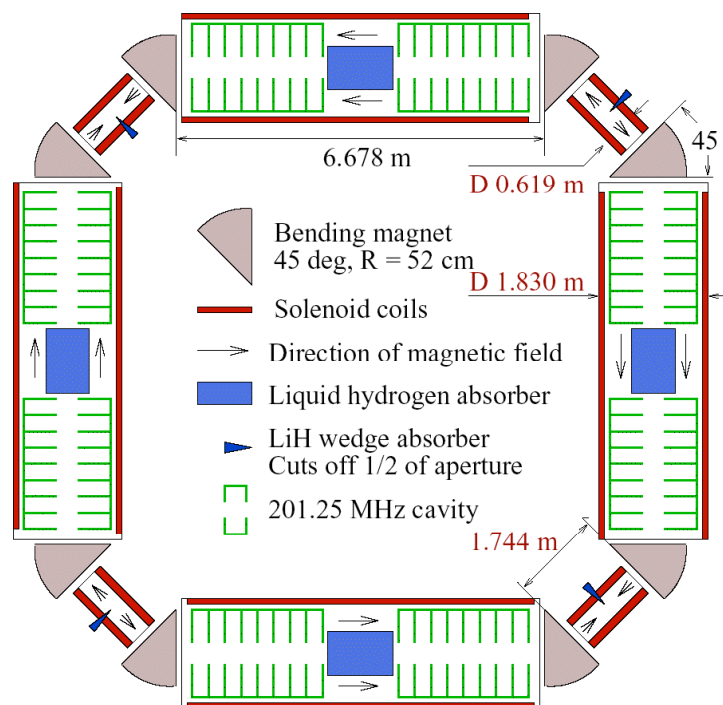
## Mucool test area at FNAL



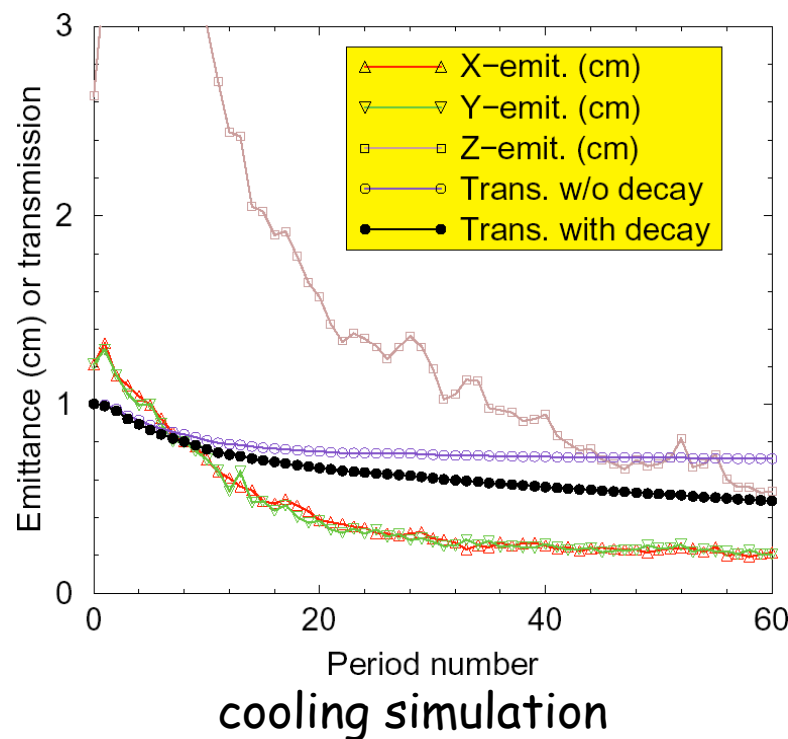
Convert existing access tunnel at FNAL  
Access to 200 MHz RF (+805 if needed)  
New cryogenics plant (recycled parts)  
Access to beam from FNAL linac  
Eventually a place to do integrated tests  
Area complete Jan. 03  
LH<sub>2</sub> filling system Jul. 03  
RF Sept. 04  
Solenoid, beam, Sept. 05



## Alternative cooling schemes



Balbekov ring



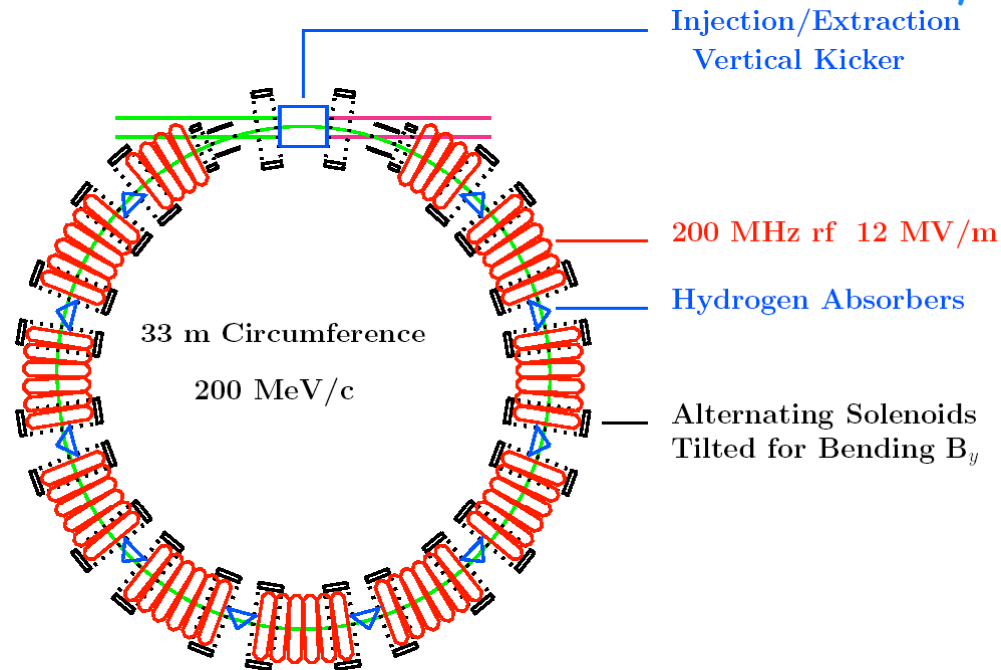
Include ring coolers, snakes and spirals etc.

Incorporate emittance exchange via wedges for 6D cooling

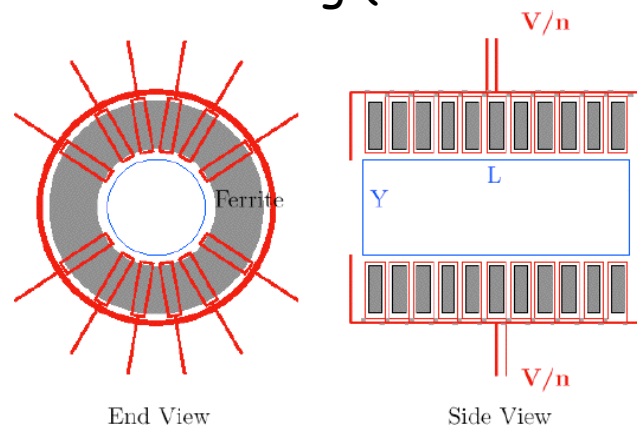
Rings offer potential savings by reusing cooling hardware on multiple passes, challenges in injection and extraction.

Very active research activity, lots of new ideas.

# Status of the Neutrino Factory and Muon Collider R&D



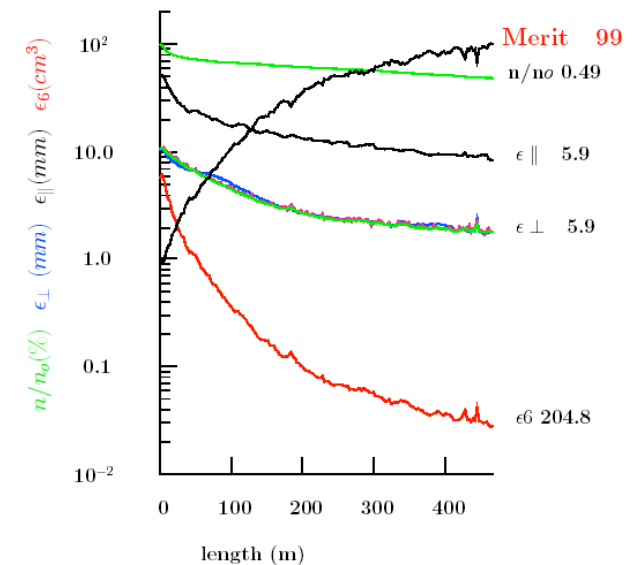
"RFOFO" ring (Palmer et al.).



## ICOOL Simulation

Input From Study 2

$n/n = 485 / 1000$

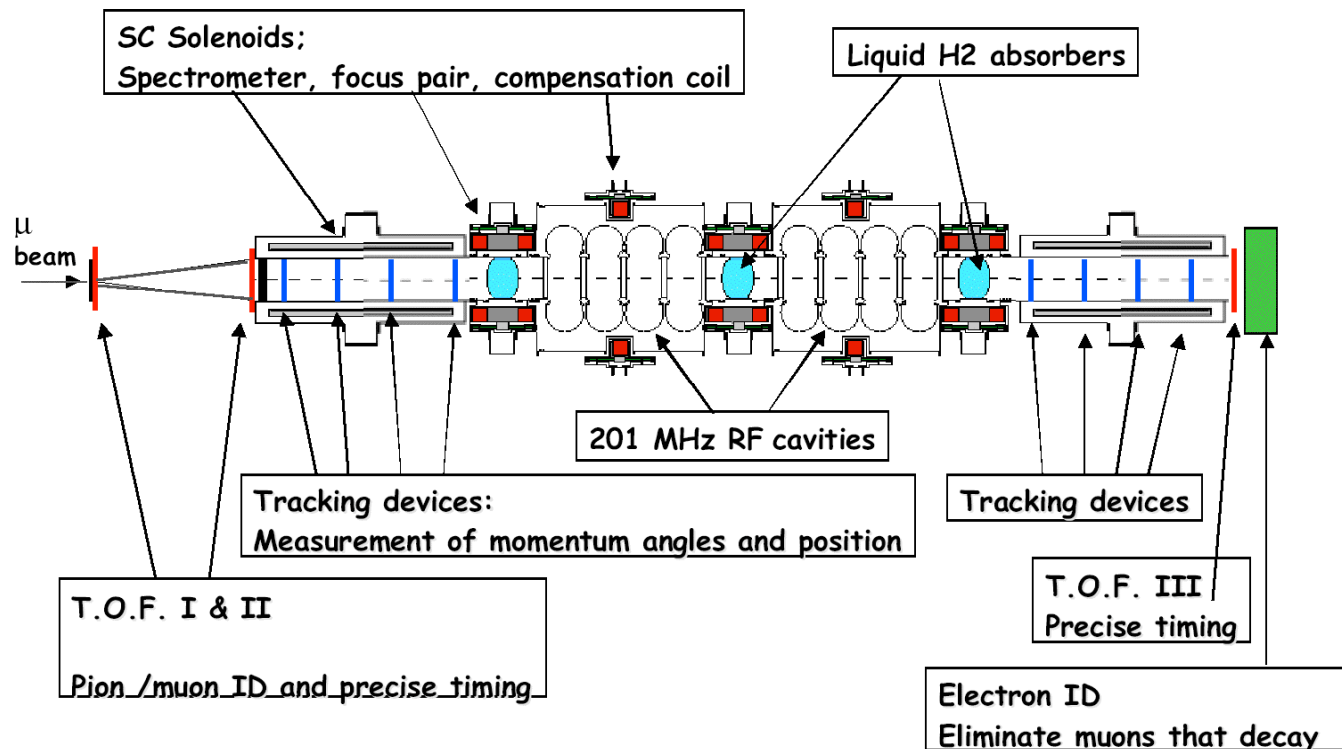


## Challenging large bore kicker

		$\mu$ Cooling	CERN $\bar{p}$	Ind Linac
$r B d \ell$	Tm	.30	.088	
L	m	1.0	$\approx 5$	5.0
$t_{\text{rise}}$	ns	50	90	40
B	T	.30	$\approx 0.018$	0.6
X	m	.42	.08	
Y	m	.63	.25	
$V_{1\text{turn}}$	kV	3,970	800	5,000
$U_{\text{magnetic}}$	J	10,450	$\approx 13$	8000



## MICE experiment



International collaboration formed to pursue muon cooling demonstration experiment

Realistic hardware as far as possible

Many complementary contributions from participating institutions

US/Japan (Mucool, MC): Absorbers, RF structures, solenoids, instrumentation

Europe: Host lab, detectors, RF power, Muon beamline

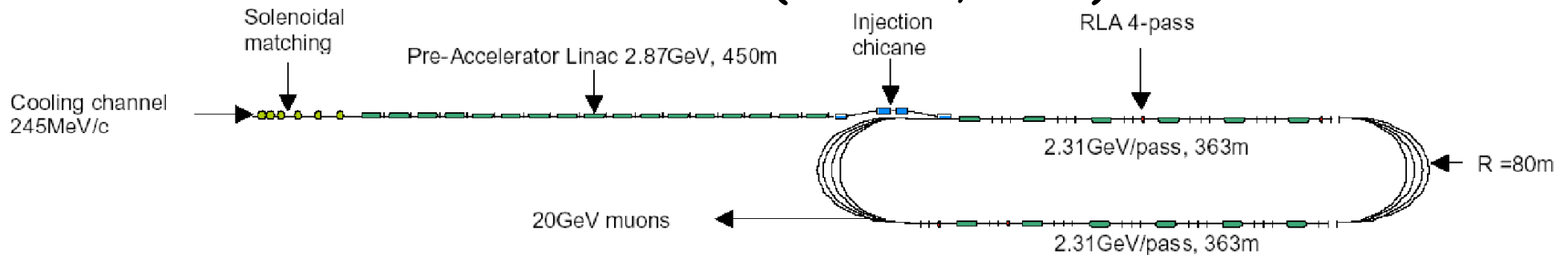
## Schedule of MICE goals and milestones

- Nov. 01 Letters of Intent to PSI, RAL
- Jan. 02 Presentation to PSI
- Mar. 02 Presentation to RAL > invitation to present full proposal
- 2002: Develop detailed technical proposal
- 2003-4: Spectrometer construction
- 2004: Spectrometer in muon beam
- 2005-6: Assembly and test of first cooling cell
- 2006-7: Assembly and test of second cooling cell

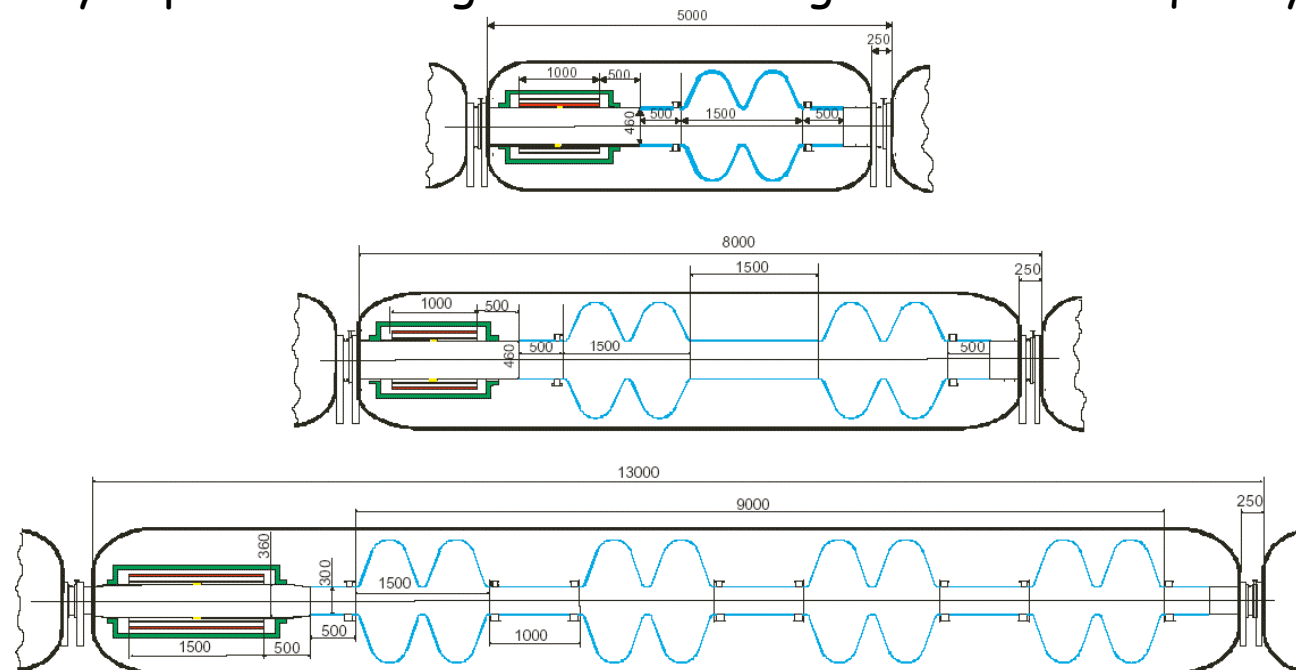
This aggressive schedule requires new funding (\$13-16M)  
(~45% from U.S.)



## Acceleration (Cornell, Jlab)

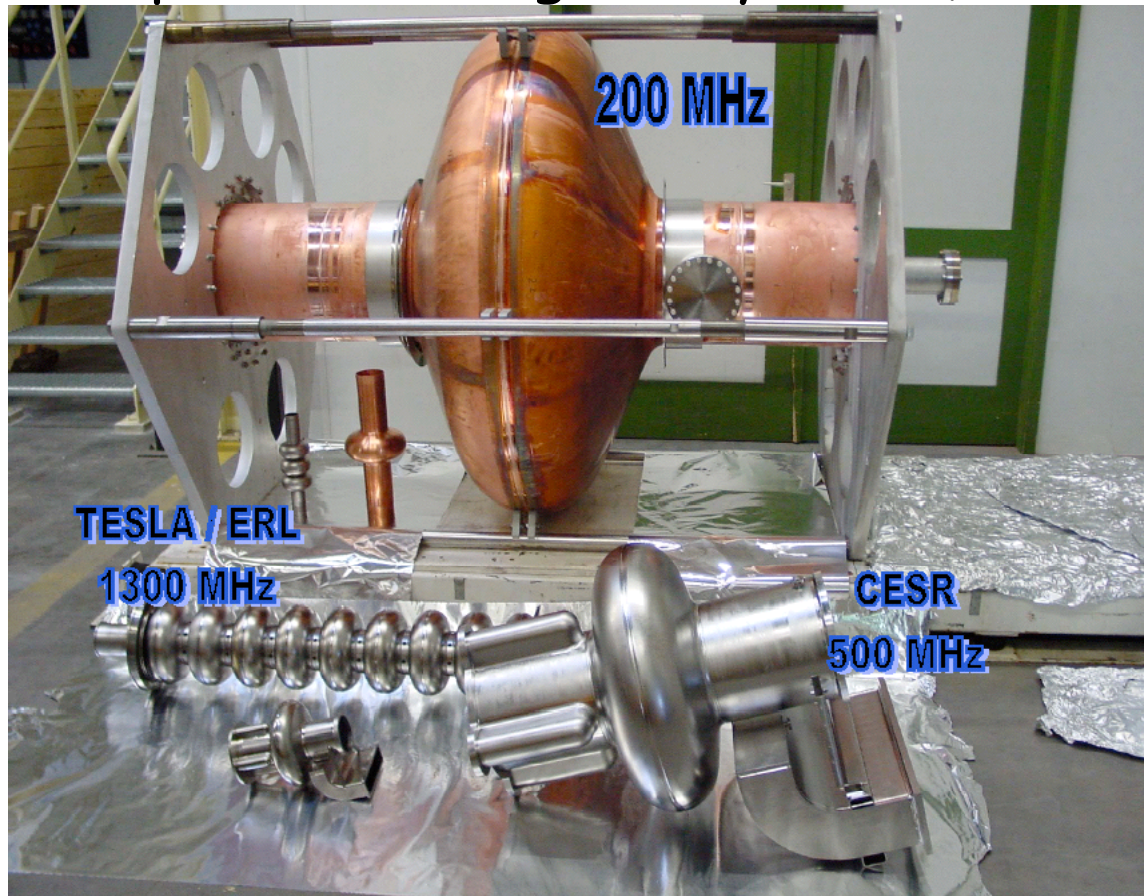


Acceleration by superconducting linac/RLA. Large bore  $\rightarrow$  low frequency (200 MHz).



Three types of cryomodule for short, medium and long lattice period.

## 200 MHz Superconducting cavity R&D (Cornell, CERN)



Expect  $Q_0 = 4.6 \times 10^9$  at 4.5 K and  $1.0 \times 10^{10}$  at 2.5 K

NbCu cavities have a "Q Slope" requiring x3 power at 15 MV/m accelerating gradient



## 200 MHz Superconducting cavity R&D (Cornell, CERN)

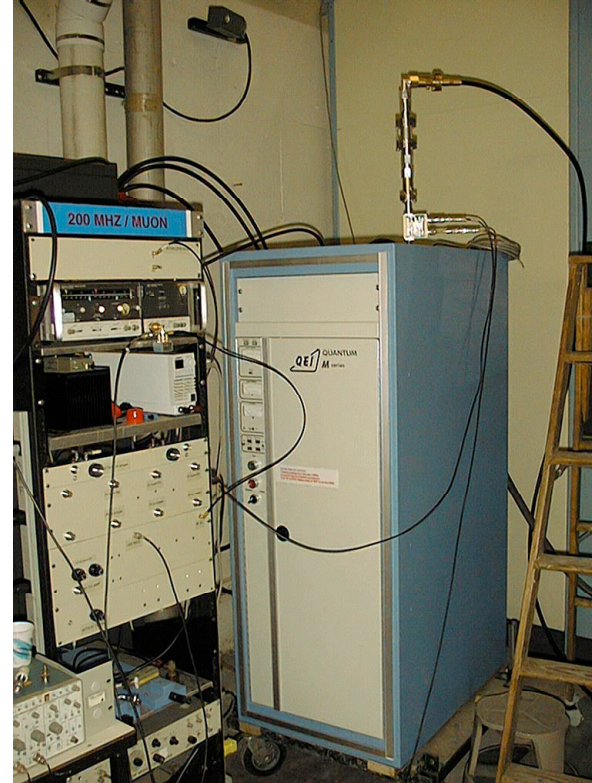


Electropolished cavity shell at CERN



New test pits at Cornell

Cavity shells fabricated in Europe, Nb sputtered at CERN, will be tested at Cornell  
At 4.5 K with 1600 W of available power, have > 600 W margin even with 430 mOe residual field at 15 MV/m.



Cornell 200 MHz test facilities

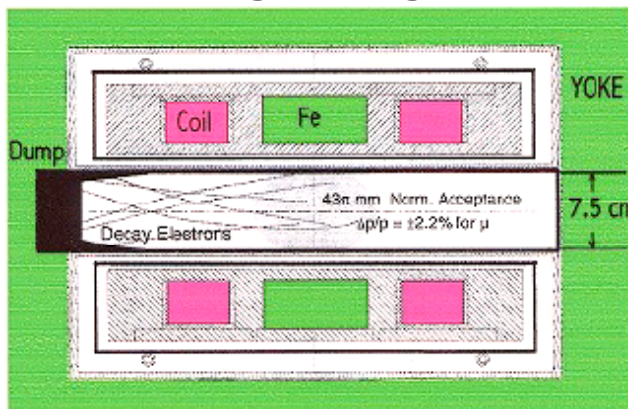
### Likely Schedule

- Mount Cavity on stand, insert in cryostat in pit, and connect to RF amplifier and instrumentation - complete by June 15.
- Cool down and test (requires 5000 liters of LHe) by end of June.
- Expect to have to recoat with Nb to reach 15 MV/m.

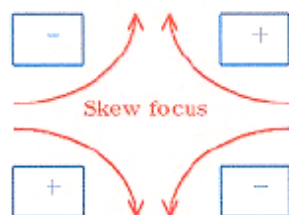


## Storage ring

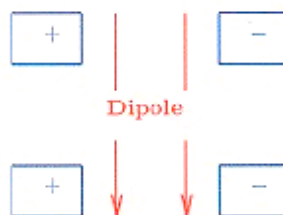
Racetrack or "Bowtie" to maximize straight length. Still relatively large bore.



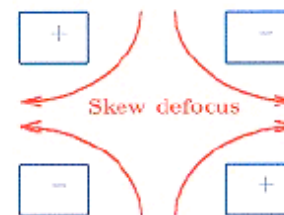
SKEW QUAD  
focus



DIPOLE



SKEW QUAD  
defocus



Overlapping coil scheme, large bore, good packing factor, avoids decay electrons

### Conclusions

We have a very active and creative collaboration that is making good progress.

Studies I and II have demonstrated feasibility.

We are aggressively pursuing the critical technologies identified by peer review:

- Targetry
- Capture and cooling
- Acceleration

Mucool, MICE and the Target experiment aim to demonstrate real functioning hardware of the type needed for a neutrino factory.

Construction could be staged with physics all the way to a muon collider.

We have a lot of support from the community. HEPAP report says:

*"We support the decision to concentrate on the development of intense neutrino sources, and recommend continued R&D near the present level of \$8M per year. This level of effort is well below what is required to make an aggressive attack on all of the technological problems on the path to a neutrino factory."*

For more information or to join the collaboration please visit:

<http://www.cap.bnl.gov/mumu/>